Planetary and Space Science 96 (2014) 81–89

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

The structure of the Venusian current sheet

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ARTICLE INFO

Article history:
Received 13 August 2013
Received in revised form
28 January 2014
Accepted 7 March 2014
Available online 20 March 2014

Keywords:
Venus Express
Venusian magnetotail
Venusian current sheet

ABSTRACT

We investigate the current sheet (CS) of the Venusian magnetotail using the data collected by the Venus Express mission in 2006–2010. We have found that the observed profiles of the main magnetic field component B_x have single-scale or double-scale structures. For single-scale CSs the B_x profile is well approximated by the Harris model, $B_0 \tanh(t/T_0)$ (T_0 is the characteristic temporal scale, B_0 is the magnetic field at the CS boundary). For double-scale CSs the B_x profile is better described by the double-scale model, $B_1 \tanh(t/T_1)+B_2 \tanh(t/T_2)$ with $B_2 > 0.3B_0$ and $T_2 > 2T_1$. The magnetic field component perpendicular to the CS plane and the shear component are on average uniform across CSs and ten times smaller than the amplitude of B_x. The observed B_x profiles can be described by the quasiadiabatic CS model. According to our interpretation the electric current in single-scale CSs is generally carried by protons on transient orbits. In double-scale CSs the current density is provided by transient protons and oxygen ions. In this case, the inner CS scale is supported by the proton population, while the outer scale is supported by the oxygen population. We suggest that the Venusian CS thickness is likely several ion thermal gyroradii.

1. Introduction

Although Venus does not have an intrinsic magnetic field (Russell et al., 1980), the interaction between the solar wind and the planetary ionosphere results in the formation of the induced magnetosphere with a well-developed magnetotail (see the review by Phillips and McComas, 1991). The mechanism of the Venusian magnetotail formation is similar to that of the formation of cometary tails (Alfven, 1957). Solar wind flux tubes are slowed down near the magnetic barrier at the day side. Convecting along the magnetic barrier, these flux tubes are mass-loaded by ionospheric oxygen ions O^+ (Cloutier et al., 1974; Taylor et al., 1980; Vaisberg and Zeleny, 1984). The parts of flux tubes passing through the barrier move slower than their ends in the solar wind. Therefore, flux tubes get stretched in the antisunward direction. The magnetotail is formed by these stretched flux tubes at the night side.

The orientation of the Venusian magnetotail is determined by directions of the solar wind flow and the interplanetary magnetic field (IMF). It is convenient to introduce the coordinate system (X, Y_B, Z_E) (Eroshenko, 1979): the X-axis is directed opposite to the solar wind flow, the Y_B-axis is along the cross-flow IMF component and the Z_E-axis is along the convective electric field. The Venus–Sun component of the magnetic field is B_x, the XZ_E plane is the magnetotail neutral plane (where $B_x=0$) and B_y is the magnetic field component perpendicular to the neutral plane. The magnetotail electric current flows in the Z_E direction, providing the B_x reversal across the neutral plane. The fundamental magnetotail element is the region of the B_x reversal, the current sheet (CS). The investigation of the Earth magnetotail have shown that the CS structure is important for the magnetotail dynamics (Baumjohann et al., 2007; Sergeev et al., 2012; Artemyev and Zelenyi, 2013). The present paper is devoted to the structure of the Venusian magnetotail CS.

The CS structure at $X \sim -10R_V$ was investigated during Pioneer Venus Orbiter (PVO) mission. McComas et al. (1986b) have shown that the average B_x profile can be described by the Harris model, i.e. $B_x \sim B_0 \tanh(y/L)$, where $B_0 \sim 15$ nT and the CS half-thickness $L \sim 1.3R_V$. B_y is on average constant across the CS and is about 4 nT

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http://dx.doi.org/10.1016/j.pss.2014.03.013
0032-0633/

(McComas et al., 1986b). We point out that the positive value of B_y is consistent with the mechanism of the magnetotail formation. In fact, the technique used by McComas et al. (1986b) substantially overestimates the CS thickness. Moore et al. (1990) have shown that the CS half-thickness does not exceed $0.25R_V$. They have also pointed out that the plasma temperature should be about 1 keV to keep the pressure balance across the CS. The CS structure at $X \sim -3R_V$ was investigated during Venera-9,10 mission. The plasma data have indicated that the CS plasma consists of protons and oxygen ions with temperatures in the range from ~ 100 eV to ~ 1 keV (see review by Vaisberg et al., 1994). However, observations of Venera-9,10 did not allow to study the CS structure on a statistical basis. The currently operating Venus Express (VEX) mission allows to fill this gap (Titov et al., 2006)

The magnetic field data of VEX (Zhang et al., 2006) has already advanced our knowledge of the Venusian CS structure at $X \sim -3R_V$. Zhang et al. (2010) have confirmed that negative B_y is frequently observed in accordance with the previous case studies (Marubashi et al., 1985). Observations of negative B_y are prescribed either to the tight flux tubes draping (Marubashi et al., 1985) or to the reconnection in the magnetotail CS (Zhang et al., 2012).

Zhang (2013) has recently determined the average B_x profile across the CS. In contrast to the distant tail CS (Moore et al., 1990), this average B_x profile has a double-scale structure and cannot be described by the Harris model. The nature of the double-scale CS structure has not been explained yet. Moreover, the averaging technique used by Zhang (2013) smooths out the peculiarities inherent to particular CS crossings, so that the actual CS structure may be more complex.

In the present paper we investigate the CS structure based on separate CS crossings by VEX and suggest the mechanism for the formation of the double-scale CS structure. We point out that measurements at one spacecraft do not allow to distinguish spatial and temporal variations of the measured magnetic field. We assume that the variation of the magnetic field observed during the CS crossing is due to the relative motion of the spacecraft and the CS, while the CS is quasi-stationary in its rest frame.

2. Data and methods

We have analyzed magnetic field data (with 4 s time resolution, Zhang et al., 2006) obtained in 2006–2010. The ion data of ASPERA-4 (with 192 s time resolution, Barabash et al., 2007) are used to determine the direction of the solar wind (SW) flow.

2.1. Selection criteria of CS crossings

The rotation of the cross-flow IMF component $\mathbf{B}_\perp$ causes the rotation of the CS neutral plane. On the other hand, the variation of the IMF component directed along the SW flow results in CS flapping motions (McComas et al., 1986b; Dubinin et al., 2012). The stationary structure of the Venusian CS can be studied if $\mathbf{B}_\perp$ does not substantially rotate during VEX residence within the tail. We determine average directions of undisturbed SW flow and IMF observed for 20 min before the inbound and for 20 min after the outbound bow shock (BS) crossings. Then we calculate the average cross-flow IMF component observed before the inbound ($\mathbf{B}_\perp^{pre}$) and after the outbound ($\mathbf{B}_\perp^{post}$) BS crossings. We have required that: (1) the angle between $\mathbf{B}_\perp^{pre}$ and $\mathbf{B}_\perp^{post}$ is smaller than 30° (Zhang et al., 2010); (2) the IMF direction is quite steady, i.e. the root mean square deviation from the average IMF direction is smaller than 20°.

The criterion (1) does not actually ensure that the CS neutral plane is steady. Indeed $\mathbf{B}_\perp$ can strongly deviate from $\mathbf{B}_\perp^{pre}$ during the tail crossing, while returns to $\mathbf{B}_\perp^{post}$ (i.e. close to $\mathbf{B}_\perp^{pre}$) just prior the outbound BS crossing. This scenario can be recognized, when $\mathbf{B}_\perp$ changes direction several times, the spacecraft then observes multiple CS crossings due to the neutral plane rotation. To exclude CS crossings observed due to this scenario, we have chosen events without multiple CS crossings. The other problem is that $\mathbf{B}_\perp$ could change just after the inbound BS crossing and remain steady during the tail crossing. The spacecraft observes then a single CS crossing, but $\mathbf{B}_\perp^{pre}$ (or $\mathbf{B}_\perp^{post}$) cannot be used to determine the CS orientation. This problem can be overcome only by means of statistical studies (Zhang et al., 2010). We have assumed that the CS orientation is determined by $\mathbf{B}_\perp^{pre}$ (or equiv. $\mathbf{B}_\perp^{post}$). We show in Section 3 that this assumption leads to results consistent with the statistical study by Zhang et al. (2010). The criterion (2) ensures that one can reliably determine the average direction of the IMF observed before and after the BS crossing.

We select CS crossings observed at $X < -1.2R_V$, and within the tail, $\sqrt{Y_B^2 + Z_E^2} < 1.3R_V$ (Zhang et al., 2010). This criterion ensures that VEX crosses the magnetotail CS rather than some CS-type structure associated with "holes" at the night side ionosphere (Brace et al., 1982). We have selected 13 CSs presented in Table 1. The locations of CS crossings and the angles between $\mathbf{B}_\perp^{pre}$ and $\mathbf{B}_\perp^{post}$ are given in Table 1.

2.2. Local coordinate system and CS flapping motion

We study each CS crossing in the local coordinate system $(\mathbf{l}, \mathbf{m}, \mathbf{n})$. The maximum variance direction $\mathbf{l}$ is determined by the

Table 1
Magnetic field data: B_n and B_m are perpendicular and shear components; $\mathbf{n}$ is the CS normal vector; γ is the angle between $\mathbf{B}_\perp^{pre}$ and $\mathbf{B}_\perp^{post}$; v_{sc} is the spacecraft velocity along the CS normal vector; (X, Y_B, Z_E) are coordinates of the CS crossing.

N	Date	B_n nT	B_m nT	$\mathbf{n}$	γ °	$\lvert v_{sc}\rvert$ km/s	(X, Y_B, Z_E) R_V
1	15 August 2006: 1:46–1:50	−0.4	0.3	(0.1,0.8,−0.59)	10	0.9	(−1.6,−0.7,0)
2	6 September 2006: 3:00–3:06	0.25	−0.6	(0.05,0.996,−0.07)	30	2.4	(−1.4,0.4,0.7)
3	30 March 2007: 5:33–5:36	2.4	2.5	(−0.05,−0.95,-0.3)	12	1.8	(−2.9,0.9,0.9)
4	5 March 2008: 4:53–5:00	−1.3	1.9	(0.07,−0.66,0.75)	12	4.2	(−2,−0.1,0.3)
5	24 October 2008: 9:05–9:13	0.4	0	(−0.2,−0.89,−0.37)	10	2.2	(−2.3,0,0.8)
6	13 September 2009: 1:42–1:48	−4.3	4.8	(−0.09,−0.99,−0.1)	25	1.3	(−2.2,0.4,0.5)
7	20 September 2009: 2:04–2:09	1.9	−0.5	(−0.06,0.87,−0.49)	1	3	(−2,0.2,−0.2)
8	11 September 2010: 8:57–9:02	3.3	0.2	(0.05,0.33,−0.94)	12	5.1	(−1.6,0.1,1)
9	31 January 2009: 7:38–7:44	0.15	−1.9	(−0.01,−0.4,0.91)	30	4.4	(−2.1,−0.1,0.5)
10	13 February 2009: 6:54–7:00	−0.13	4.3	(−0.11,−0.95,0.3)	10	1.9	(−1.7,−0.1,−0.3)
11	6 March 2009: 5:29–5:33	5.1	1.9	(−0.1,0.69,−0.72)	30	6.7	(−1.2,0.5,1.1)
12	26 May 2009: 1:59–2:08	0.1	1.6	(0,0.93,0.35)	12	2.5	(−1.5,0,0.5)
13	1 March 2008: 4:48–4:55	1.7	−0.9	(−0.05,0.86,0.51)	16	3.4	(−1.6,−0.1,0.4)